

Observation of the ${}^7_{\Lambda}\text{He}$ hypernucleus by the $(e, e'K^+)$ reaction

S. N. Nakamura,¹ A. Matsumura,¹ Y. Okayasu,¹ T. Seva,² V. M. Rodriguez,³ P. Baturin,⁴ L. Yuan,⁵ A. Acha,⁴ A. Ahmidouch,⁶ D. Androic,² A. Asaturyan,⁷ R. Asaturyan,⁷ O. K. Baker,⁵ F. Benmokhtar,⁸ W. Boeglin,⁴ P. Bosted,⁹ R. Carlini,⁹ C. Chen,⁵ M. Christy,⁵ L. Cole,⁵ S. Danagoulian,⁶ A. Daniel,³ V. Dharmawardane,⁹ K. Egiyan,⁷ M. Elaasar,¹⁰ R. Ent,^{9,5} H. Fenker,⁹ Y. Fujii,¹ M. Furic,² L. Gan,¹¹ D. Gaskell,⁹ A. Gasparian,⁶ E. F. Gibson,¹² T. Gogami,¹ P. Gueye,⁵ Y. Han,⁵ O. Hashimoto,¹ E. Hiyama,¹³ D. Honda,¹ T. Horn,⁸ B. Hu,¹⁴ Ed V. Hungerford,³ C. Jayalath,⁵ M. Jones,⁹ K. Johnston,¹⁵ N. Kalantarians,³ H. Kanda,¹ M. Kaneta,¹ F. Kato,¹ S. Kato,¹⁶ D. Kawama,¹ C. Keppel,^{5,9} L. Kramer,⁴ K. J. Lan,³ W. Luo,¹⁴ D. Mack,⁹ K. Maeda,¹ S. Malace,⁵ A. Margaryan,⁷ G. Marikyan,⁷ P. Markowitz,⁴ T. Maruta,¹ N. Maruyama,¹ T. Miyoshi,³ A. Mkrtchyan,⁷ H. Mkrtchyan,⁷ S. Nagao,¹ T. Navasardyan,⁷ G. Niculescu,¹⁷ M.-I. Niculescu,¹⁷ H. Nomura,¹ K. Nonaka,¹ A. Ohtani,¹ M. Oyamada,¹ N. Perez,⁴ T. Petkovic,² S. Randeniya,³ B. Raue,⁴ J. Reinhold,⁴ R. Rivera,⁴ J. Roche,⁹ Y. Sato,¹⁸ E. K. Segbefia,⁵ N. Simicevic,¹⁵ G. Smith,⁹ Y. Song,¹⁴ M. Sumihama,¹ V. Tadevosyan,⁷ T. Takahashi,¹ L. Tang,^{5,9} K. Tsukada,¹ V. Tvaskis,⁵ W. Vulcan,⁹ S. Wells,¹⁵ S. A. Wood,⁹ C. Yan,⁹ and S. Zhamkochyan⁷

(HKS (JLab E01-011) Collaboration)

¹Graduate School of Science, Tohoku University, Sendai, Miyagi 980-8578, Japan

²Department of Physics & Department of Applied Physics, University of Zagreb, HR-41001 Zagreb, Croatia

³Department of Physics, University of Houston, Houston, Texas 77204, USA

⁴Department of Physics, Florida International University, Miami, Florida 33199, USA

⁵Department of Physics, Hampton University, Virginia 23668, USA

⁶Department of Physics, North Carolina A&T State University, Greensboro, North Carolina 27411, USA

⁷Yerevan Physics Institute, Yerevan 0036, Armenia

⁸Department of Physics, University of Maryland, College Park, Maryland 20742, USA

⁹Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA

¹⁰Department of Physics, Southern University at New Orleans, New Orleans, LA 70126, USA

¹¹Department of Physics, University of North Carolina Wilmington, Wilmington, NC 28403, USA

¹²Physics and Astronomy Department, California State University, Sacramento CA 95819, USA

¹³Institute for Physical and Chemical Research (RIKEN), Wako, Saitama 351-0198, Japan

¹⁴Nuclear Physics Institute, Lanzhou University, Lanzhou, Gansu 730000, China

¹⁵Department of Physics, Louisiana Tech University, Ruston, Louisiana 71272, USA

¹⁶Faculty of Science, Yamagata University, Yamagata 990-8560, Japan

¹⁷Department of Physics, James Madison University, Harrisonburg, Virginia 22807, USA

¹⁸Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki 305-0801, Japan

(Dated: August 28, 2012)

An experiment with a newly developed high-resolution kaon spectrometer (HKS) and a scattered electron spectrometer with a novel configuration was performed in Hall C at Jefferson Lab (JLab). The ground state of a neutron-rich hypernucleus, ${}^7_{\Lambda}\text{He}$, was observed for the first time with the $(e, e'K^+)$ reaction with an energy resolution of ~ 0.6 MeV. This resolution is the best reported to date for hypernuclear reaction spectroscopy. The ${}^7_{\Lambda}\text{He}$ binding energy supplies the last missing information of the $A = 7, T = 1$ hypernuclear iso-triplet, providing a new input for the charge symmetry breaking (CSB) effect of ΛN potential.

PACS numbers: 21.80.+a, 21.60.Cs, 25.30.Rw, 27.20.+n

A hypernucleus contains a hyperon implanted as an impurity within the nuclear medium. The lightest hyperon is the Λ particle (uds, isospin 0). Precise information about the mass and excitation energies of hypernuclei allows one to infer the underlying hyperon-nucleon interaction, which is not yet well known. In contrast to nucleon-nucleon scattering, hyperon-nucleon (YN) scattering experiments are technically difficult and data is very limited.

The study of hypernuclei seeks to extend our knowledge of the nuclear force and baryon-baryon forces in general. While the strange quark is heavier than up and down quarks, it is light enough to be treated in

the framework of $\text{SU}(3)_{\text{flavor}}$ symmetry, a natural extension of isospin symmetry for nucleons. Understanding of baryon-baryon forces based on $\text{SU}(3)_{\text{flavor}}$ symmetry is important to bridge between phenomenologically well studied nuclear force models and the underlying degrees of freedom of the strong interaction as described by Quantum Chromodynamics (QCD).

Since a single Λ inside a nucleus is not subject to the Pauli Exclusion Principle, it can occupy any accessible shell, including the deeply bound s-shell in the heaviest nuclei. The Λ decays only by the weak interaction with a relatively long lifetime (~ 260 ps). As the widths of hypernuclear energy levels are typically less than a few

100 keV, spectroscopic study of these systems is possible. The Λ can also probe the interior structure of the host nucleus. Furthermore, one can search for possible modifications of the composition and structure of deeply bound baryons.

After the first observation of a Λ hypernucleus more than a half century ago with an emulsion [1], meson beams such as K^- and π^+ have been widely used to obtain spectroscopic information via missing mass analysis in the ${}^A Z(K^-, \pi^-){}_\Lambda^A Z$ and ${}^A Z(\pi^+, K^+){}_\Lambda^A Z$ reactions. In both of these reactions, Λ hyperons are produced off neutrons, which precludes the use of the elementary reaction channel for an accurate mass calibration. Together with the inherently limited quality of these secondary meson beams, the accuracy of absolute mass determinations has been limited to a resolution of no better than 1.5 MeV.

The ${}^A Z(e, e'K^+){}_\Lambda^A(Z-1)$ reaction produces strangeness by $s\bar{s}$ pair-production, similar to the (π^+, K^+) reaction. An interesting feature of the $(e, e'K^+)$ reaction is that it converts a proton to a Λ enabling us to calibrate the absolute missing mass scale by using the $p(e, e'K^+)\Lambda, \Sigma^0$ reaction with the well known masses of the Λ and Σ^0 hyperons. Furthermore, the $(e, e'K^+)$ reaction can produce new species of hypernuclei and thus the charge dependence of hypernuclei can be studied by comparing $(e, e'K^+)$ hypernuclear spectroscopy to already known iso-multiplet partners. As well as the above unique features, $(e, e'K^+)$ hypernuclear reaction spectroscopy has the potential for good (sub-MeV) energy resolution due to the availability of primary electron beams with lower energy spread than available for secondary meson beams.

We report here the first clear observation of the ground state of ${}^7_\Lambda\text{He}$ through the ${}^7\text{Li}(e, e'K^+){}^7_\Lambda\text{He}$ reaction. Although ${}^7_\Lambda\text{He}$ has been observed in emulsion experiments [2], only a total of 11 events are known; furthermore, the measured masses for these events are spread out widely, which lead to speculation that long lived isomeric states [3–5] were observed together with the ground state. Therefore, no ground state mass has been quoted in the literature.

${}^7_\Lambda\text{He}$ is the missing member of the $A = 7, T = 1$ isospin triplet, the other two being ${}^7_\Lambda\text{Li}^*$ and ${}^7_\Lambda\text{Be}$. The three core nuclei ${}^6\text{He}$, ${}^6\text{Li}^*$, and ${}^6\text{Be}$ have in common an α -core, surrounded by a halo nucleon pair, nn , pn , and pp , respectively. Likewise, the bound Λ wave function is predicted to reach far beyond the α -core and thus have a significant overlap with the halo nucleon pair [6]. In particular, ${}^7_\Lambda\text{He}$ plays a key role in the study of the halo structure of neutron-rich hypernuclei since it has a core of the lightest bound neutron-halo nucleus ${}^6\text{He}$.

As suggested by Hiyama *et al.*, this iso-triplet is the perfect testing ground to study the Charge Symmetry Breaking (CSB) effect in the ΛN potential. The binding energies of the iso-triplet were recently computed using a four-body cluster model with the CSB effect [6]. A ΛN CSB potential was phenomenologically introduced

to explain the binding energy difference of the $A = 4$ iso-doublet ($T = 1/2$) hypernuclei ${}^4_\Lambda\text{H}$ and ${}^4_\Lambda\text{He}$. The difference $B_\Lambda({}^4_\Lambda\text{He}) - B_\Lambda({}^4_\Lambda\text{H}) = +0.35 \pm 0.06$ MeV is unexpectedly large even after corrections due to the Coulomb interaction.

The experimental challenge of $(e, e'K^+)$ hypernuclear reaction spectroscopy originates from the small hypernuclear production cross section and high backgrounds. The cross section of the $(e, e'K^+)$ reaction is ≤ 100 nb/sr which is two-three orders of magnitude smaller than that of hadronic production. Furthermore, the $(e, e'K^+)$ reaction requires two spectrometers for a coincidence between scattered electrons and kaons. These experimental difficulties result in lower hypernuclear yields and poorer signal-to-noise ratios than meson reactions.

The pilot experiment E89-009 (HNSS), performed at Jefferson Lab (JLab) in 2000, demonstrated the principle of $(e, e'K^+)$ hypernuclear spectroscopy [7, 8]. The experiment showed that ${}^{12}\text{C}(e, e'K^+){}^{12}_\Lambda\text{B}$ spectroscopy with sub-MeV resolution is possible with the high quality electron beam at JLab, but it also showed that improvements were possible to fully exploit the potential of hypernuclear study by electro-production. The 10^{-3} momentum resolution and small solid angle of the kaon spectrometer (SOS) limited the resolution and hypernuclear yield. In E89-009, zero-degree electrons were measured to maximize the virtual photon yield, but this also reduced the signal-to-noise ratio thus limiting the beam current and target thickness that could be used.

The natural extension to the E89-009 experiment is the E01-011 experiment (HKS) performed in JLab's Hall C in 2005 [9] from which the spectrum discussed here was obtained. In the E01-011 experiment, a high reso-

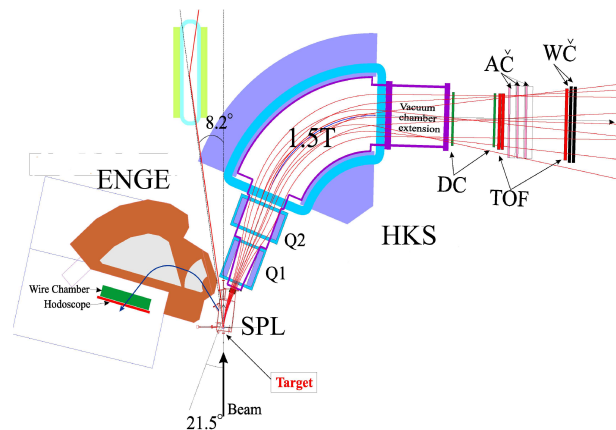


FIG. 1. Schematic figure of the E01-011 experimental setup. A newly constructed HKS (High resolution Kaon Spectrometer) and an ENGE-type split pole spectrometer (ENGE) which was also used in E89-009 were used as the kaon and scattered electron spectrometers. The ENGE was vertically tilted to suppress background originating from Bremsstrahlung and Møller scattering.

lution ($\Delta p/p \sim 2 \times 10^{-4}$) kaon spectrometer (HKS) was constructed and an existing electron spectrometer was optimized to improve the resolution and hypernuclear yield over the E89-009 experiment. The improvements allowed the system to handle 180 times higher luminosity (4.5 times thicker target and 40 times stronger electron beam) with 100 times smaller electron background rate in ENGE spectrometer.

Figure 1 shows a layout of the experimental setup. The target was placed in a dipole magnet (SPL) which separated the oppositely charged particles at small forward angles. The K^+ s were measured by the HKS which has a central momentum of $P_K = 1.2$ GeV/ c and a 16 msr solid angle when used with the SPL magnet. The scattered electrons (central momentum $P_{e'} = 0.35$ GeV/ c) were measured by the ENGE-type split-pole spectrometer which was vertically tilted by 8 degrees from the dispersion plane and shifted vertically by an amount to suppress electron backgrounds originating from Bremsstrahlung and Møller scattering which have very sharp forward distributions (tilt method). The electron beam energy was set at $E_e = 1.851$ GeV giving a virtual photon energy of about 1.5 GeV ($\simeq E_e - cP_{e'}$). The typical beam current for the lithium target was 25 μ A. Details of the design of the experiment will be explained elsewhere [10]. Since the beam energy from CEBAF at JLab was known with an accuracy of $1 \times 10^{-4} \sim 180$ keV, measurements of the momentum vectors of K^+ and e' at the target were sufficient to obtain the missing mass of the hypernuclei. The positions and angles of the scattered kaons and electrons were measured at the focal planes of the HKS and ENGE spectrometers. These focal plane quantities were converted to target momentum vectors using backward transfer matrices of the spectrometers. The initial transfer matrices were generated by using a GEANT4 Monte Carlo simulation with three-dimensional magnetic field maps obtained by field measurement and finite element calculation by Opera-3D (TOSCA). The backward transfer matrices were obtained from these initial transfer matrices and tuned using calibration data such as the sieve slit data which constrains the angular parts of the matrices, and the Λ and Σ^0 peaks from the $p(e, e'K^+)\Lambda, \Sigma^0$ reaction with protons in a CH_2 target, constraining the the momentum parts of the matrices.

Figure 2 shows the missing mass spectrum from scattering off a CH_2 target with clear peaks corresponding to Λ and Σ^0 hyperon production off of protons and an underlying background from quasi-free hyperon production on carbon and accidental coincidences between e 's and K^+ s. The accidental background shape was obtained very precisely by randomly selecting uncorrelated e 's and K^+ s (mixed events analysis). The Λ and Σ^0 peak positions were used for missing mass calibration and the backward transfer matrix tunes. The tuned and calibrated matrices gave the peak positions in table I. The miss-

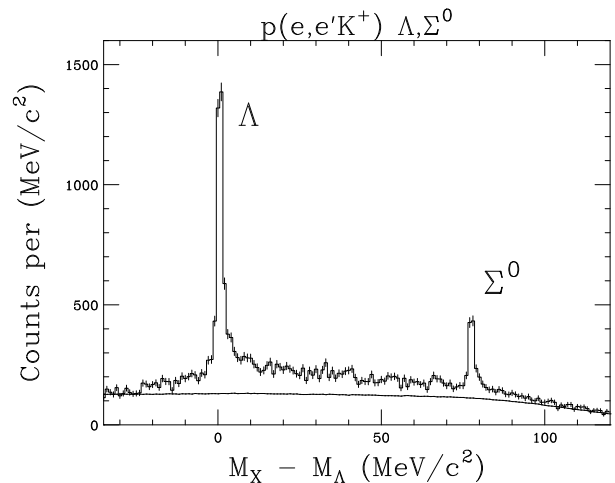


FIG. 2. Missing mass spectrum of $p(e, e'K^+)\Lambda/\Sigma^0$ reaction. Mass of Λ particle was subtracted. Λ , Σ^0 peaks were used to calibrate the absolute missing mass scale. The line shows the accidental background estimated by the mixed events analysis method.

ing mass scale was calibrated for these hyperons within a 100 keV uncertainty. The widths of hyperon peaks are worse than the expected sub-MeV resolution for hypernuclei because hyperons are much lighter than hypernuclei and kinematic broadening due to finite angular resolution of spectrometers contributed more significantly to the energy resolution.

In the E01-011 experiment, a natural Li target of 189 mg/cm² (⁷Li abundance 92.4%), was used as a target. The measured missing mass was converted to binding energy using:

$$-B_\Lambda = M({}^7_\Lambda\text{He}) - (M_\Lambda + M({}^6\text{He})),$$

and plotted in figure 3. A ⁶He mass of 5605.537 MeV/ c^2 was obtained from the reported mass excess [12].

The accidental coincidence events in figure 3 were estimated by using the mixed events technique. After subtraction of the accidental background and correction of the spectrometers' acceptance and detector efficiencies, the number of counts was converted to the differential cross section averaged over the acceptances of HKS ($1.05 < P_K < 1.35$ GeV/ c , $1^\circ < \theta_K < 13^\circ$). Since the virtual photon is almost real ($Q^2 \sim 0.01$ GeV²/ c^2 , $W \sim 1.9$ GeV), the $(e, e'K^+)$ differential cross section was converted to the differential cross section for virtual photons

TABLE I. Λ and Σ^0 masses: M_Y (PDG values) and M_X fitted values of E01-011 data. Unit of values is MeV/ c^2 .

Hyperon	M_Y [11]	$M_X - M_Y$	Width (FWHM)
Λ	1115.683	0.09 ± 0.02	1.94 ± 0.45
Σ^0	1192.642	0.05 ± 0.03	1.87 ± 0.56

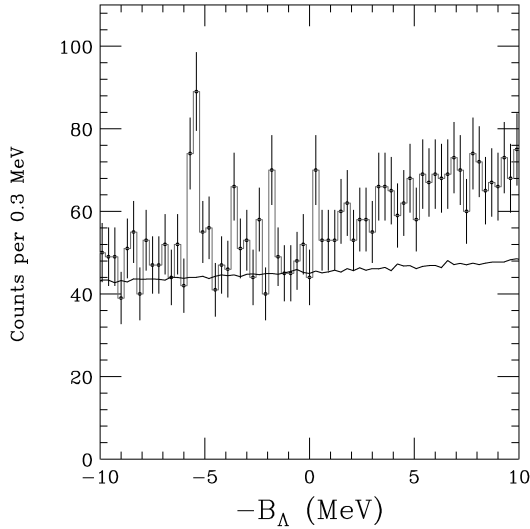


FIG. 3. Binding energy spectrum obtained by the ${}^7\text{Li}(e, e'K^+){}^7_\Lambda\text{He}$ reaction. The line shows the accidental background estimated by the mixed events analysis method.

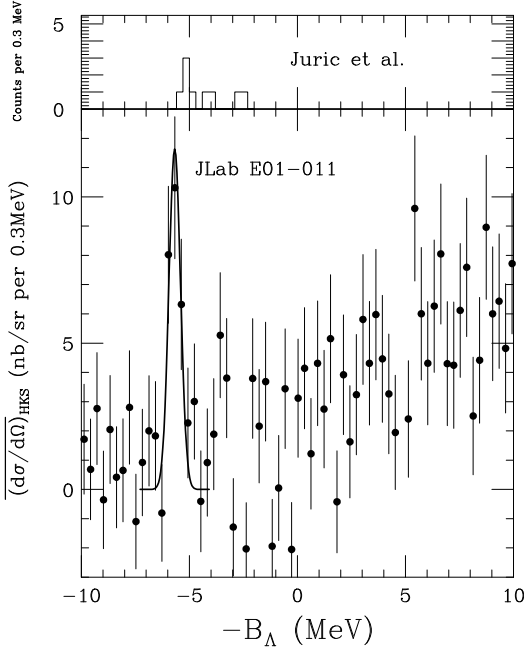


FIG. 4. Binding energy spectra of ${}^7_\Lambda\text{He}$ measured by the emulsion experiment [2] (top) and the JLab E01-011 (HKS) experiment after background subtraction and acceptance corrections (bottom).

using the virtual photon flux (Γ) as:

$$\frac{d\sigma}{d\Omega_K} = \frac{1}{\Gamma} \frac{d\sigma}{dE_{e'} d\Omega_{e'} d\Omega_K}.$$

The virtual photon flux integrated over the ENGE acceptance ($0.24 < P_{e'} < 0.44$ GeV/c, $\Delta\Omega_{e'} = 5.6$ msr) was 4.8×10^{-6} virtual photons per electron.

Figure 4 shows the ${}^7_\Lambda\text{He}$ spectra measured by the emulsion experiment (top) [2] and by JLab E01-011 (bottom). The E01-011 spectrum shows a clear peak which corresponding to the ${}^7_\Lambda\text{He}$ ground state ($1/2^+$). There exists some structure between the ground state and the threshold ($B_\Lambda = 0$), but the statistics are not enough to discuss in detail. The systematic error of binding energy due to the tuning processes of the transfer matrices was estimated by applying the analysis procedures to the dummy data generated by a full Monte Carlo simulation with arbitrarily chosen hypernuclear masses and various signal-to-noise ratios (S/N). The simulated data were analyzed using the same software as the real data and the arbitrarily chosen hypernuclear masses were hidden from the analysis group. The difference between the inputs to the simulation and the analysis results were treated as the systematic error due to the matrix tuning processes. The estimated systematic error depends on S/N. For major peaks (S/N > 0.3), the error was less than 100 keV, but for poor S/N peaks (S/N < 0.3), the error would be as large as 400 keV. Other sources of systematic error on the binding energy are uncertainties in kinematic parameters such as the absolute electron beam energy and the central momenta of the K^+ and e' . Their contributions were studied carefully and estimated to be less than 150 keV. The systematic errors to the cross section were estimated with the same method in addition to the beam current uncertainty.

The ground state peak of ${}^7_\Lambda\text{He}$ was fitted by a Gaussian and, the binding energy and cross section for virtual photon were obtained as:

$$\begin{aligned} -B_\Lambda &= -5.68 \pm 0.03(\text{stat.}) \pm 0.25(\text{sys.}) \text{ MeV}, \\ \left(\frac{d\sigma}{d\Omega}\right)_{\text{HKS}} &= 26 \pm 5.1(\text{stat.}) \pm 9.9(\text{sys.}) \text{ nb/sr}, \end{aligned}$$

with a width of 0.63 ± 0.12 MeV (FWHM).

The E01-011 experiment successfully observed the ${}^7_\Lambda\text{He}$ ground state with sufficient statistics. The emulsion data show a cluster with a broad tail (Fig. 4 top) and the binding energy was not obtained [2]. It was hypothesized that the cluster corresponded to the ground state and that the broad tail originated from decay of isomeric states of ${}^7_\Lambda\text{He}$ but this was not experimentally confirmed [3–5]. The E01-011 data are consistent with the interpretation that the cluster of emulsion data corresponds to the ground state.

The binding energies of the ${}^7_\Lambda\text{Be}$ and ${}^7_\Lambda\text{Li}$ ground states were measured by emulsion [2] but the ground state of ${}^7_\Lambda\text{Li}$ is the $T = 0$ state ($B_\Lambda({}^7_\Lambda\text{Li}, T = 0) = 5.58 \pm 0.03$ MeV) [2]. Therefore, the energy spacing information from the γ -ray measurement, $Ex(T = 1, 1/2^+) = 3.88$ MeV [13] and the excitation energy of ${}^6\text{Li}^*(T = 1) = 3.56$ MeV were used to calculate the binding energy of ${}^7_\Lambda\text{Li}^*(T = 1)$ state.

The binding energies of $A = 7$, $T = 1$ iso-triplet hypernuclei, ${}^7_\Lambda\text{He}$, ${}^7_\Lambda\text{Li}^*$, ${}^7_\Lambda\text{Be}$, now experimentally measured

are shown in table II.

TABLE II. Binding energies of $A = 7, T = 1$ iso-triplets Λ hypernuclei. Errors of E01-011 are statistical and systematic errors.

	${}^7_\Lambda\text{He}$ (E01-011)	${}^7_\Lambda\text{Li}^*$ [2, 13]	${}^7_\Lambda\text{Be}$ [2]
B_Λ (MeV)	$5.68 \pm 0.03 \pm 0.25$	5.26 ± 0.03	5.16 ± 0.08

The binding energies of these hypernuclei were calculated by Hiyama *et al.* based on an $\alpha + N + N + \Lambda$ four-body cluster model with a normalized three-body ΛNN force [6] and a CSB potential which was phenomenologically introduced to explain the mass difference of the $A = 4, T = 1/2$ Λ hypernuclear doublet (${}^4_\Lambda\text{H}$ and ${}^4_\Lambda\text{He}$). Since ${}^6\text{Be}$, the core nucleus of ${}^7_\Lambda\text{Be}$, is unbound, the calculation of ${}^7_\Lambda\text{Be}$ may suffer from a larger ambiguity while the ground state of ${}^6\text{He}$ is a two-neutron halo bound state, which is the core nucleus of ${}^7_\Lambda\text{He}$. Therefore, experimental input of ${}^7_\Lambda\text{He}$ binding energy is quite important to constrain the theory. In addition, a system with an unbound core + Λ is quite interesting to study Λ 's glue like role in hypernuclei such as the ground state of ${}^7_\Lambda\text{Be}$ and the core excited states of ${}^7_\Lambda\text{He}$. The $A = 4$ hypernuclear iso-doublet, ${}^4_\Lambda\text{H}$ and ${}^4_\Lambda\text{He}$, determined the even part of the phenomenologically introduced CSB term in the ΛN potential but information from p-shell hypernuclei is necessary to constrain the odd part of it. The binding energies of the $A = 7$ hypernuclear iso-triplet provide such information though the expected energy shift of the CSB potential is about 0.2 MeV which is almost the same as the systematic error of the present measurement.

The $(e, e'K^+)$ hypernuclear spectroscopy technique was established at JLab by the present E01-011 experiment in Hall C and an independent experiment (E94-107) performed in Hall A [14, 15]. The experimental studies of hypernuclei and strangeness production with electron beams have continued to improve with the JLab E05-115 experiment [16] and a recently initiated program at the upgraded MAMI-C, Mainz University [17, 18].

Theoretical studies of light hypernuclei with the CSB ΛN potential are also proceeding. The phenomenological CSB potential which took the $A = 7, T = 1$ hypernuclear iso-triplet into account was used to calculate $A = 10$ hypernuclear iso-doublet by applying the same calculation technique to $\alpha + \alpha + N + \Lambda$ system [19, 20]. The E05-115 experiment at JLab will provide the binding energy of ${}^{10}_\Lambda\text{Be}$ using the ${}^{10}\text{B}(e, e'K^+){}^{10}_\Lambda\text{Be}$ reaction. The systematic errors in E01-011 are expected to be improved upon in the E05-115 analysis since additional calibration data were taken with a new high-resolution electron spectrometer (HES).

Since the binding energy difference between ${}^4_\Lambda\text{H}$ and ${}^4_\Lambda\text{He}$ hypernuclei is the starting point of CSB discussions, new measurements with recent experimental tech-

niques are necessary. A binding energy measurement of ${}^4_\Lambda\text{H}$ is planned at both JLab and MAMI-C by using the ${}^4\text{He}(e, e'K^+){}^4_\Lambda\text{H}$ reaction and there are plans to use the newly proposed decay π spectroscopy of hyperfragments [21] and hypernuclear γ -ray experiment of ${}^4_\Lambda\text{He}$ at J-PARC [22]. More precise data on ${}^7_\Lambda\text{He}$ and ${}^{10}_\Lambda\text{Be}$ from JLab E05-115 and the planned experiments on $A = 4$ hypernuclei will provide definitive experimental information to determine the CSB terms in the ΛN potential.

We acknowledge continuous support and encouragement from the staff of the Jefferson Lab physics and accelerator divisions. The hypernuclear programs at JLab Hall-C are supported by Japan-MEXT Grant-in-aid for Scientific Research (16GS0201, 15684005, 12002001, 08239102, 09304028, 09554007, 11440070, 15204014), Japan-US collaborative research program, Core-to-core program (21002) and strategic young researcher overseas visits program for accelerating brain circulation (R2201) by JSPS, US-DOE contracts (DE-AC05-84ER40150, DE-FG02-99ER41065, DE-FG02-97ER41047, DE-AC02-06CH11357, DE-FG02-00ER41110, DE-AC02-98-CH10886) and US-NSF (013815, 0758095).

-
- [1] M. Danysz and J. Pniewski, *Phyl. Mag.* **44**, 348 (1953).
 - [2] M. Juric *et al.*, *Nucl. Phys.* **B 52** (1973) 1.
 - [3] J. Pniewski and M. Danysz, *Phys. Lett.* **1** 143 (1962).
 - [4] R.H. Dalitz and A. Gal, *Nucl. Phys.* **B1** 1 (1967).
 - [5] J. Pniewski *et al.*, *Nucl. Phys.* **B2** 317 (1967).
 - [6] E. Hiyama, Y. Yamamoto, T. Motoba and M. Kamimura, *Phys. Rev.* **C 80** (2009) 054321.
 - [7] T. Miyoshi *et al.*, *Physical Review Letter* **90** (2003) 232502.
 - [8] L. Yuan *et al.*, *Physical Review* **C 73** (2006) 044607.
 - [9] O. Hashimoto, L. Tang, J. Reinhold, S.N. Nakamura *et al.*, JLab E01-011 Proposal (2001).
 - [10] to be submitted to *Nucl. Inst. and Meth.*
 - [11] K. Nakamura *et al.* (Particle Data Group), *J. Phys.* **G37**, 075021 (2010).
 - [12] G. Audi, A.H. Wapstra and C. Thibault, *Nucl. Phys.* **A729** 337 (2002).
 - [13] H. Tamura *et al.*, *Phys. Rev. Lett.* **C 84** (2000) 5963.
 - [14] F. Cusanno *et al.*, *Phys. Rev. Lett.* **103** (2009) 202501.
 - [15] F. Cusanno *et al.*, *Nucl. Phys.* **A 835** (2010) 129.
 - [16] O. Hashimoto, S.N. Nakamura, L. Tang, J. Reinhold *et al.*, JLab E05-115 Proposal (2005).
 - [17] P. Achenbach *et al.*, *Nucl. Phys.* **A 835** (2010) 313.
 - [18] P. Achenbach *et al.*, *Nucl. Phys.* **A 881** (2012) 187.
 - [19] E. Hiyama *et al.*, *Prog. Theor. Phys.* Vol.**128** No.1 (2012) in press.
 - [20] Y. Zhang, E. Hiyama, Y. Yamamoto, *Nucl. Phys.* **A 881** (2012) 288.
 - [21] L. Tang, A. Margaryan, S.N. Nakamura, J. Reinhold, L. Yuan, F. Garibaldi, J. LeRose *et al.*, JLab E10-001 proposal (2010).
 - [22] H. Tamura *et al.*, J-PARC E13 proposal (2007).